Defense Technical Information Center Compilation Part Notice

ADP013088

TITLE: STM Investigation of a Strong Electric Field Effect on Local Photocurrent Spectra in InAs/GaAs Quantum Dot Heterostructures

DISTRIBUTION: Approved for public release, distribution unlimited
Availability: Hard copy only.

This paper is part of the following report:

TITLE: Nanostructures: Physics and Technology International Symposium [8th] Held in St. Petersburg, Russia on June 19-23, 2000 Proceedings

To order the complete compilation report, use: ADA407315

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP013002 thru ADP013146

8th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 19–23, 2000

STM investigation of a strong electric field effect on local photocurrent spectra in InAs/GaAs quantum dot heterostructures

V. Ya. Aleshkin, A. V. Biryukov, S. V. Gaponov, V. M. Danil'tsev, *V. L. Mironov*, A. V. Murel and V. I. Shashkin
Institute for Physics of Microstructures RAS, 603600, Nizhny Novgorod, Russia

Abstract. We demonstrate a possibility of using a scanning tunneling microscope (STM) for a high spatial resolution study of photocurrent spectra of quantum-dimensional structures. The effect produced by an electric field on the position and intensity of the size quantization levels maxima in the local photocurrent spectra for InAs/GaAs structures with quantum dots located near the sample surfase is investigated.

Introduction

The probe microscopy methods are being widely used currently for high spatial resolution investigations into the properties of quantum-dimensional structures based on InGaAs/GaAs. Major success in this research has been achieved in the study of local luminescence by the use of near-field optical microscopy [1, 2] and electroluminescence in the STM tunneling contact (the so-called STM-cathodoluminescence) [3–5]. When applied quantum dot structures, these techniques allows observation of narrow lines in the luminescence spectra, which correspond to the transitions between the levels of size quantization in single dots. The drawback common for all of the above methods, however, is in low-temperature requirement to enable observation of local luminescence and, besides, the condition that a quantum well or a quantum dot layer must be outside the region of a GaAs space charge, otherwise the electric field would separate the charges in the near-surface layer thus impending recombination process. This would degrade space resolution, since the actual probing area increases through diffusion of nonequilibrium carriers.

A promising method for detecting the local photocurrent spectra by STM was offered recently in [6]. It allows investigation of the excited states in the energy spectrum of quantum-dimensional objects located immediately near the sample surface. In this case the field of a surface space charge separates the electron-hole pairs generated by photoexcitation so that spatial resolution in this methods depends mainly on the surface rather than volume diffusion of carriers, which is less intensive. For quantum dots located near the sample surface the spatial resolution can, in principle, be brought to the size of the wavefunction of minority carriers localized on a single quantum dot.

In this paper we report the results obtained in the STM studies of the electric field effect on the spectra of local photocurrent in InAs/GaAs quantum dot heterostructures.

1. Experiment

The structures were MOCVD-grown on GaAs substrates [7]. A layer of quantum dots was located near a sample surface. The GaAs covering layer thickness was 1.5–2 nm. To avoid oxidation, the samples were immersed in vacuum oil immediately after growth, so the photocurrent spectra were taken from the tunneling contact realized through an oil film. In experiments we used a scanning tunneling microscope of our own design,

which is combined with an optical system [8]. The structures were of n-type conductivity, with an STM current-voltage characteristic (I–V characteristic) that was typical of a metal-semiconductor tunneling contact. The probe was held over a surface via a feedback system of STM operating at j_t = const and a voltage corresponding to the forward branch of the I–V characteristic. Photocurrent was defined as the difference between the current in the backward branch of the I–V curve for an illuminated contact and the dark current. A 100 W halogen lamp radiation transmitted through the monochromator and a passive optical filter to cut off the visible part of spectrum was used for an optical pumping of samples. The monochromatic radiation was carried to a semiconductor structure by a multicable lightguide from the back side of the substrate which provided additional filter to cut off the quanta of light with energies higher than the GaAs band gap. Due to this arrangement photocarriers were generated only in the epitaxial layer of InAs/GaAs. The spectral dependence of photocurrent were plotted from the data overaged over 100 measurement results.

2. Results and discussion

As demonstrated in the experiments, the spectral dependence of a local photocurrent contain a number of peaks corresponding to the carrier transitions between different states of the energy spectrum of a quantum-dimensional structure. A characteristic STM spectrum of a photocurrent is shown in Fig. 1(a). The first short-wave peak with the energy of about 1.397 eV appears to result from carbon impurity contained in the GaAs layer of a MOCVD grown structure. Its energy corresponds to that of transition between the acceptor level which is by 26 meV higher than the valence band top, and the conductivity band. As follows from the calculations, the interband transition energy in a wetting layer of InAs (one monolayer thick) is 1.377 eV at room temperature, which is in good agreement with the value for the second peak in the photocurrent spectra. The peaks in the long-wave part of the spectra seem to be related to the transitions from the excited hole states of a quantum dot to the electron levels in the wetting layer and to the levels of the excited electron states in a quantum dot.

A study was carried out on the effect produced by an electric field on the position and intensity of peaks in the STM-yelded spectra of photocurrent, corresponding to size quantization levels. The spectral dependences of a local photocurrent in quantum-dot structures for different values of bias voltage at a tunneling gap contact are shown in Fig. 1(b). They exhibit a few features. In the short-wave part of the spectrum ($\lambda \leq 950$ nm) the peaks become more intensive and broader with a higher voltage. A different situation is observed for the spectral components in the long-wave part of spectrum ($\lambda \geq 950$ nm). An increase in voltage therein lessens intensity of the peaks and simultaneously causes them to broaden. The intensity of the first peak corresponding to the transition of carriers from the acceptor level of carbon to the GaAs conductivity band increases, and the peak shifts towards the long-wave of the spectrum.

A higher local photocurrent in the short-wave region of spectrum can be accounted for by the Franz–Keldysh effect in a bulk GaAs layer lying closest to a tunneling contact, where electric fields are strong. Indeed, the light absorption in a strong electric field gets higher, due to the tunneling of charge carriers, in the region of quantum energies lower than the band gap [9]. It reaches a maximum near the fundamental absorption edge and falls off exponentially with a decreasing photon energy. A similar increase of photocurrent in this spectral region is also observed for structures without quantum objects, where it is caused by the electric field effect on the electron states in bulk GaAs.

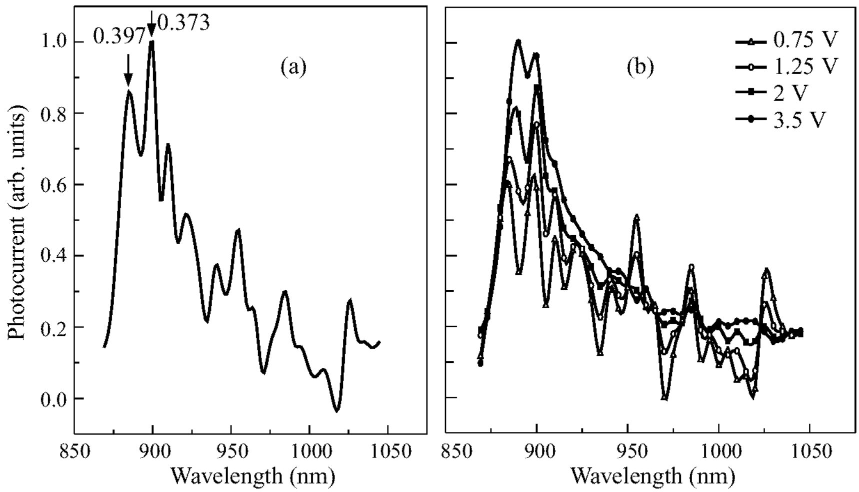

Fig. 1. (a) Tipical STM spectra of local photocurrent in InAs/GaAs structure with quantum dots located near a sample surface. Thickness of the GaAs cap layer is about 1.5 nm. (b) STM spectra of local photocurrent in InAs/GaAs structure with quantum dots located near a sample surface for different values of bias voltage at a tunneling gap contact.

A completely different effect is produced by an electric field on the intensity of optical transitions between localized states. In a strong electric field the mean coordinates of the electron and hole localized states of a quantum dot shift in opposite directions, thereby reducing the overlaping integral of the wave functions for the initial and final states and, hence, the probability of optical transition between them. Besides, the electric field delocalizes localized states, since there appears a non-zero probability of tunneling transition to the continuous spectrum states. As a result, the corresponding absorption lines intensity lessens, and the lines become blurred. The blurring of a line depends on the time of an electron tunneling from a localized state to a continuous spectrum state. It is nicely seen in Fig. 1(b) that the peaks in the spectral region corresponding to transitions involving the localized states of a quantum dot become smaller and broader with higher voltage and practically vanish at $V = 3.5$ V. The latter is likely to imply that the frequency of tunnel escape from the excited states involved in absorption at this voltage becomes comparable with the value equal to the localization energy divided by the Planck constant, so the states actually become delocalized.

3. Conclusion

STM aided investigations into the effect of a strong electric field on the local photocurrent spectra in InAs/GaAs structures with quantum dots located near a sample surface are reported. It is shown that a higher photoresponse in the short-wave region of spectrum is due to the Franz–Keldysh effect, whereas the intensity lessening for peaks in the long-wave region of spectrum of photocurrent and the peaks broadering may be accounted for by the influence of an electric field on the wavefunction of excited localized states in quantum dots.

Acknowlegements

The authors are thankful to D. Volgunov, D. Revin and O. Khrykin for assistance in this work. This work was supported by the National program “Fundamental metrology” (project

No 3.45) and the RFBR grants Nos 98-02-16625, 99-02-16139 and 00-02-16486.

References

[1] T. D. Harris, D. Gershoni, *et al.*, *Semicond. Sci. Technol.* **11**, 1569 (1996).

[2] A. Chaves-Pirson, J. Temmo, *et al.*, *Appl. Phys. Lett.* **72(26)**, 3494 (1998).

[3] M. Markmann, A. Zrenner, *et al.*, *Phys. Status Solidi (a)* **164(301)**, 301 (1997).

[4] M. Grundmann, J. Christen, *et al.*, *Phys. Rev. Lett.* **74(20)**, 4043 (1995).

[5] J. Lindahl, M.-E. Pistol, *et al.*, *Appl. Phys. Lett.* **68(1)**, 60 (1996).

[6] V. Ya. Aleshkin, A. V. Biryukov, *et al.*, *Pis'ma Zh. Tekh. Fiz.* **26(1)**, 3 (2000).

[7] V. Ya. Aleshkin, D. M. Gaponova, *et al.*, *Semiconductors* **32(1)**, 111 (1998).

[8] D. G. Volgunov, S. V. Gaponov, *et al.*, *Instruments and Experimental Techniques* **41(2)**, 123 (1998).

[9] A. I. Ansel'm, *Vvedenie v Teoriyu Poluprovodnikov*, (M: Nauka) 1978.